$PSNR_{r,f}$: Assessment of Delivered AVC/H.264 Video Quality over 802.11a WLANs with Multipath Fading

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Abstract— Emerging as the method of choice for compressing video over WLANs, the AVC/H.264 standard is a suite of coding options and parameters whose values are to be chosen for specific videos and channel conditions. We investigate the delivered quality of AVC/H.264 coded video across the video characteristics, the quantization parameter (QP), the group of picture size (GOPS), the payload size (PS), PHY data rate in 802.11a, and average channel signal to noise ratio (SNR). We show that the delivered quality of a coded video sequence varies tremendously across the frames per channel realization, and across different channel realizations of the same PHY data rate at the same average channel SNR. The performance also varies across different average channel SNRs and combinations of codec parameters. We propose a statistical video quality indicator $PSNR_{r,f}$ defined as peak SNR (PSNR) achieved by $f\%$ of the frames in each one of the $r\%$ of the realizations. We study the correspondence between $PSNR_{r,f}$ and perceptual video quality through a subjective experiment and employ $PSNR_{r,f}$ to assess video communications performance under various channel conditions.

I. INTRODUCTION

Recently there has been a significant interest in using packetized video over WLANs. The assessment of the delivered video quality is critical for designing, evaluating and improving, in a cross-layer manner, the video compression schemes, the physical layer (PHY) configuration and the 802.11 protocols and access schemes. Perceptual quality measurement of video sequences has been a very active research area but no universally effective objective metric has been standardized [1]. The objective metrics that have been proposed are computationally very expensive. The measurement of video quality is made even more complicated by packet losses in WLANs with frequency selective multipath fading and the packet loss concealment schemes embedded in the video codecs.

The Advanced Video Coding (AVC) standard, designated ITU-T H.264 and MPEG-4 Part 10, offers a coding efficiency improvement by a factor of two over previous standards and its network abstraction layer (NAL) transports the coded video data over networks in a more "network-friendly" way [2].

Because of these two features, the AVC/H.264 standard is emerging as the method of choice for video coding over WLANs.

In this paper, we investigate the performance of AVC/H.264 coded video for IEEE 802.11a WLANs in a frequency selective multipath fading environment. The AVC/H.264 standard is a suite of coding options and there are many important choices of parameters to be made for communication over wireless LANs with the IEEE 802.11 protocols and access schemes. Therefore we code several video sequences using combinations of parameter values for the three dominant parameters in the codecs: group of picture sizes (GOPSs), quantization stepsizes which are indexed by quantization parameters (QPs), and video payload sizes (PSs). An extensive set of packet loss realizations are generated for a physical layer (PHY) data rate of 6 Mbps, different average channel SNRs (3.5 dB for bad channel, 5 dB for average channel, 7 dB for good channel at 6 Mbps), and two PSs (small–100 bytes and large–1100 bytes). A small set of tests for additive white Gaussian noise (AWGN) channel are also conducted for comparison. Three different videos coded using combinations of GOPSs (10, 15, 30, 45 frames), QPs (26 for refined quantization and 30 for coarse quantization) and PSs are processed based on the packet loss patterns generated by the channel. In the medium access control (MAC) layer of IEEE 802.11, a cyclic redundancy check (CRC) is computed over the entire packet, and if a single bit error is detected, the packet is discarded. For data, a retransmission would be requested, however, for video we do not request a retransmission, but rely on packet loss concealment.

We show that the delivered quality of a coded video sequence varies tremendously across the frames per channel realization, and across different channel realizations of the same PHY data rate at the same average channel SNR. Therefore average bit error rate (BER) or packet error rate (PER) is not a good choice for designing adaptation schemes (Section III).

We propose a statistical video quality indicator $PSNR_{r,f}$ as PSNR achieved by $f\%$ of the frames in each one of the $r\%$ of the realizations. This quantity has the potential to capture the performance loss due to damaged frames in a particular video sequence ($f\%$), as well as to indicate the probablity of

a user experiencing a specified quality over the channel ($r\%$). The percentage of realizations also has the interpretation of what percentage out of many video users would experience a given video quality. We study the correspondence between $PSNR_{r,f}$ and perceptual video quality through a subjective experiment and compare $PSNR_{r,f}$ to the average PSNR across all the frames and channel realizations (Section IV). We employ $PSNR_{r,f}$ to assess the delivered video quality in each average channel condition. AWGN channels are also tested for comparison (Section V).

II. Background

A. Video quality asssessment

The methods of measuring perceptual video quality are usually divided into two categories: subjective measurements and objective measurements. Subjective video quality measurements have been conducted under standardized International Telecommunication Union (ITU) Recommendations ITU-T P.910 [3] and ITU-R BT.500 [4]. Subjective measurements involve a huge number of experiments on human subjects so they are expensive and time-consuming. The most commonly used objective video quality metric is the mean squared error (MSE) or equivalently the PSNR of the distorted videos. A number of sophisticated objective video quality metrics have been proposed in the past few years based on the lower order processing of human vision systems (HVS) [1], [5], [6]. These sophisticated objective metrics focus on quantifying the quality degradation due to the artifacts caused by compression and therefore they correlate to human perception more precisely than PSNR.

However for video over WLANs, the quality degradation in the video encoder is overwhelmed by the quality degradation caused by the possible packet losses in the wireless channel, even though the losses are concealed to some extent in the decoders. If for a single frame, the PSNR of the compressed signal is known and it is also known that the reconstructed frame without errors has acceptable video quality for the application, the PSNR of the frame reconstructed at the decoder after transmission through the channel can be a useful indicator of performance. However when the PSNRs vary significantly across the frames in a video sequence, which we will show is the case for delivered video with packet losses, the assessment of the overall quality of this video sequence is unclear. Furthermore in the scenario when the quality a video user experiences is not deterministic or the scenario when multiple users are using the same channel, the assessment of the channel in terms of the delivered video quality has not been studied.

B. Choices in AVC/H.264 codecs

Figure 1 is a simplified diagram of a typical AVC/H.264 encoder, with the options for the major schemes and parameters presented in the callout blocks. Some of these options are new in AVC/H.264 such as "9 intra-frame prediction modes" and "different block sizes", while others are inherited from the older standards but with refinements. Each video sequence has its unique properties and the codec parameters must be chosen

accordingly. For example, in Table I we show that the average PSNR, source bit rate and intra-predicted frame and inter-predicted frame sizes are quite different for three different video sequences at two values for QP. These videos are coded using AVC/H.264 reference software [7] JM10.1 with GOPS = 90 frames, frame rate = 15 frames per second (fps), 5 reference frames, and no packet loss. This suggests that to derive an indicator of delivered AVC/H.264 video quality, a collection of video sequences needs to be coded using combinations of different values for the codec parameters.
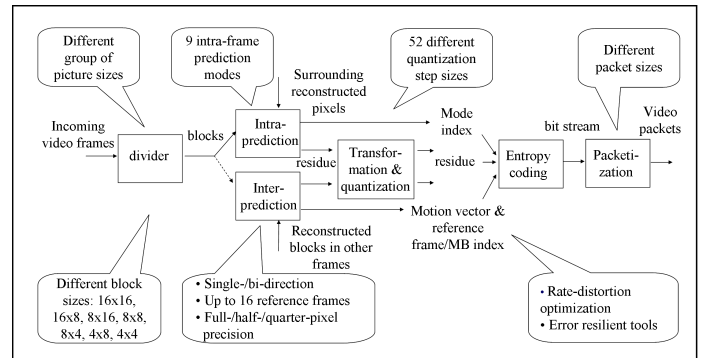

Fig. 1. Simplified diagram of AVC/H.264 encoder with different coding options and parameters

TABLE I
AVC/H.264 CODEC PERFORMANCE OF THREE DIFFERENT VIDEO SEQUENCES

Video	silent.cif		paris.cif		stefan.cif	
Typical application	video conference		news broadcast		sports broadcast	
QP	26	30	26	30	26	30
Average PSNR	36.69	34.22	36.59	33.45	36.69	33.47
Bit rate (kbps)	169.5	97.8	373.5	218.9	1396.8	404.6
I frame size (bytes)	13945	8826	19886	14390	30432	15978
Average of P frame size (bytes)	1272	725	2924	1683	11429	3230
Variance of P frame size (bytes)	412	254	322	219	1544	625

C. Link adaptation in IEEE 802.11a

The IEEE 802.11a wireless systems operate in the 5 GHz Unlicensed National Information Infrastructure (U-NII) band. It uses twelve 20 MHz channels from the U-NII lower-band (5.15-5.25 GHz), U-NII mid-band (5.25-5.35 GHz) and U-NII upper-band (5.725-5.825 GHz) with the first 8 channels dedicated for indoor use. Each 20 MHz channel is composed of 52 subcarriers, with 48 being used for data transmission and the remaining 4 used as *pilot carriers* for channel estimation and phase tracking needed for coherent demodulation. The 802.11a PHY provides 8 modes with varying data rates from 6 to 54 Mbps by using different modulation and coding schemes as shown in Table II. Forward error correction (FEC) is done

TABLE II
PHY MODES IN IEEE 802.11A

Mode	Modulation	Code Rate	Data Rate	Bytes per Symbol
1	BPSK	1/2	6 Mbps	3
2	BPSK	3/4	9 Mbps	4.5
3	QPSK	1/2	12 Mbps	6
4	QPSK	3/4	18 Mbps	9
5	16-QAM	1/2	24 Mbps	12
6	16-QAM	3/4	36 Mbps	18
7	64-QAM	2/3	48 Mbps	24
8	64-QAM	3/4	54 Mbps	27

by using a rate 1/2 convolutional code and bit interleaving for the mandatory rates and using puncturing for the higher rates. A detailed description of OFDM systems and applications to wireless LANs can be found in [8], [9].

The OFDM physical layer convergence procedure (PLCP) is used for controlling frame exchanges between the MAC and PHY layers. The frame format for the MAC data frame is given in Fig. 2. Each MAC frame or MAC protocol data unit (MPDU) consists of MAC header, variable length frame body and a frame check sequence (FCS). The MAC header and FCS consists of 28 bytes and the ACK is 14 bytes long. The frame body varies from 0-2304 bytes including the RTP/UDP and IP headers. The RTP and UDP overhead for multimedia traffic is 12 and 8 bytes, respectively, and another 20 bytes is added for the IP header. A PLCP Protocol Data Unit (PPDU) is formed by adding a PLCP preamble and header to the MPDU. The PLCP header (excluding the service field) is transmitted using BPSK modulation and rate 1/2 convolutional coding. The six "zero" tail bits are used to unwind the convolutional code, i.e. to reset it to the all zero state, and another 16 bits is used by the SERVICE field of the PLCP header.
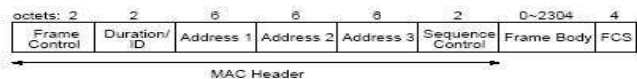
Fig. 2.   Frame format of a data frame MPDU

Most link adaptation schemes target data transmission [10], [11], as opposed to voice and video. In [11] the expected effective throughput is expressed as a closed-form function of the data payload length and the selected data transmission rate as a function of channel SNR in AWGN and Nakagami fading environments. A joint selection of data rate and payload length is done to maximize the user throughput without retransmissions. In [12], joint PHY-MAC based link adaptation schemes to maximize throughput and achieve a PER constraint for frequency selective multipath fading channels are proposed. However, the connection between PER and concealed video quality is not taken into account by these link adaptation schemes. The cross-layer adaptation schemes for video communications proposed in [13], [14] model distortion in the video as a function of the average BER or PER of the wireless channels without consideration of the effects of the variation in BER or PER on the video quality and they exclude the different options in the source codecs for adaptation.

III. VIDEO OVER WLAN SETUP

We investigate the performance of AVC/H.264 coded video across the video characteristics, the quantization parameter (QP), the group of picture size (GOPS), the payload size (PS), PHY data rate in 802.11a, and the average channel SNR for multipath fading channels. The wireless channel model used for the multipath fading case is the Nafteli Chayat model [15], which is an important indoor wireless channel model with an exponentially decaying Rayleigh faded path delay profile. The rms delay spread used was 50 nanoseconds which is typical for home and office environments. Each realization of the multipath delay profile corresponds to a certain loss pattern for that fading realization. Figure 3 plots the effective throughput and PER for the different IEEE 802.11a PHY data rates at an SNR of 3 dB for additive white Gaussian noise. One intuitive design is to choose the PS that maximizes the effective throughput, such as, for example, about 1100 bytes in Figure 3(a). However, this optimal PS corresponds to a possibly large PER of 10% in Figure 3(b), which might not yield acceptable video quality. To compare the results of using different PSs, we choose 1100 bytes as the large PS, which is close to the optimal PS for throughput maximization under the conditions in Figure 3, and 100 bytes as the small PS, which yields much lower throughput but also much lower PER.
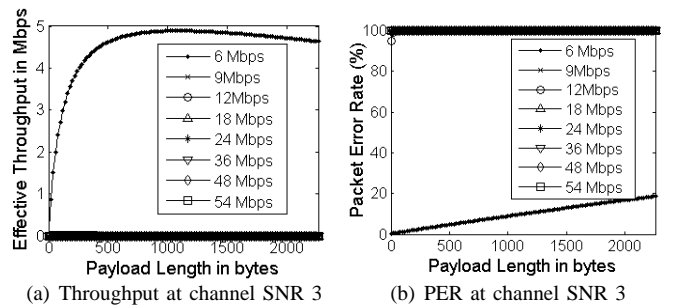
(a) Throughput at channel SNR 3   (b) PER at channel SNR 3

Fig. 3.   Effective throughput and PER for at a SNR of 3 dB for IEEE 802.11a PHY rates

Figure 4 plots the cumulative distribution function (cdf) of PER for 100 byte and 1100 byte packets in a multipath fading environment at average channel SNRs of 3.5 dB, 5 dB and 7 dB when the 6 Mbps PHY data rate is used. It shows that for the same channel SNR and the same PS, the PER of an individual channel realization can range from 0% to 100%, with the 1100 byte packets more likely to be lost than the 100 byte packets. Roughly, at most a 10% packet loss in video can be concealed for acceptable quality. Note from Figure 4 that for a PS of 100 bytes and an average SNR = 7 dB, the average PER across the realizations is 5.5%, but this PER is achieved by only 90% of the realizations. Thus 10% of the realizations will have a higher PER than the average. The cdf of PER for 100 byte packets and 6 Mbps PHY data rate in an AWGN environment at a channel SNR of 0.5 dB is also plotted. It shows that the average PER of an AWGN channel is much lower than that of a multipath fading channel even at a much poorer channel SNR. Also the variation of the PER of an AWGN channel is significantly lower as we can see that all PERs of the AWGN channel in this figure vary only from 1% to 3%.

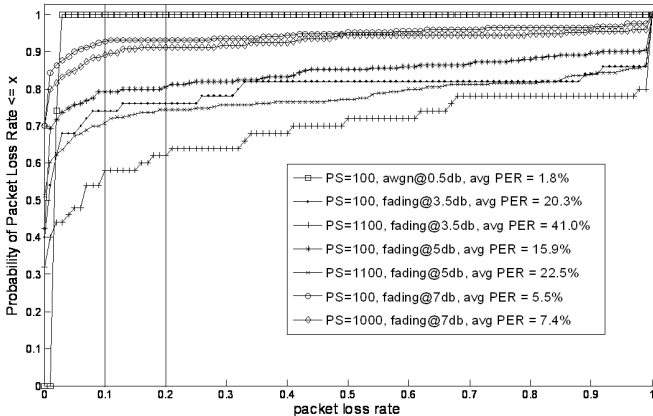We are mainly concerned with real-time two-way video-

Fig. 4. Cumulative distribution function (cdf) of packet error rate of different channels in AWGN and multipath fading environments for 100 byte and 1100 byte packets and PHY data rate as 6 Mbps

conferencing in which round-trip delay of video needs to be less than 500 ms and the coding complexity needs to be low. Therefore the Baseline Profile with forward-only inter-frame prediction is chosen in the simulations and we are interested in not requiring any retransmissions. 90 frames of each of three videos, silent.cif, paris.cif and stefan.cif are processed at 15 fps and the number of reference frames is fixed as 5. The latest version of AVC/H.264 reference software [7] JM10.1 is used, including its packet loss concealment implementation. The three dominant parameters – QP, GOPS and PS are tested for different values. QP dominates the quantization error and has a major effect on the coded video data rate. GOPS determines the intra-frame refresh frequency and plays an important role when there is packet loss. PS is the parameter that is carried forward from the source to the PHY layer. The remainder of the adjustable parameters in Figure 1: the intra-mode, block size and inter-frame prediction precision are optimally chosen in the encoder to yield the minimum source bit rate. 250 packet loss patterns are generated for each of the investigated combinations of average channel SNR, video PS and PHY data rate.

We obtain a PSNR for each frame and each packet loss pattern, for a combination of the codec parameters. Figure 5 plots the PSNRs of each frame of the video silent.cif coded at QP = 26 and 30, GOPS = 15, PS = 100 for 100 realizations of multipath fading channel of average SNR 7 dB and AWGN channel of SNR 3 dB, respectively, when PHY data rate 6 Mbps is used. The thick lines in each plot represent the average PSNRs across the 100 realizations. It is clear that even for the same video, coded using the same parameters for the same average channel SNR, the quality of concealed video in terms of PSNR varies significantly across different realizations. This is typical for all of the videos and parameters we tested. PSNRs also can vary dramatically from one frame to another in the same processed video sequence. From Figure 4 we know that for the multipath fading channel about 70% of the realizations have no packet loss. These realizations overlap and form the lines marked with "+" in Figure 5(a) and 5(c). For the AWGN channel each realization has similar PERs. However, because of the prediction employed in video coding,

it is shown in Figures 5(b) and 5(d) that the realizations of similar PER can generate completely different concealed video quality. The AWGN channel with a smaller SNR does not deliver better video quality than the multipath fading channel. This suggests that neither the average PER, nor the average PSNR across all the frames and all the realizations, is a suitable indicator of the quality a video user experiences and therefore these quantities should not serve as the basis for developing or evaluating video communications schemes for WLANs.

IV. DEFINITION OF $PSNR_{r,f}$ AND ITS CORRESPONDENCE TO PERCEPTUAL QUALITY

In this section we propose a statistical PSNR based measure $PSNR_{r,f}$ which is defined as the PSNR achieved by $f\%$ of the frames in each one of the $r\%$ of the realizations. This definition is based on two observations that are recognized by researchers in this area [6]: 1) the frames of poor quality in a video sequence dominate human viewers' experience with the video; 2) When the PSNRs are higher than a threshold, increasing PSNR does not correspond to an increase in perceptual quality that is already excellent at the threshold. Only PSNR of the luminance component of the video sequences are considered and the peak signal amplitude picked in this paper is 255 due to 8 bit precision in the video codecs.

Parameter r captures the reliability of a channel and can be set as a number between 75% to 100% according to the desired consistency of the user experience. To study the correlation between $PSNR_{r,f}$ and the perceptual quality of videos and to find a suitable range for the parameter f, a subjective experiment is designed and conducted. Stimulus-comparison methods [4] are used in this experiment, where two video sequences of the same content were presented to the subjects side by side and were played simultaneously. The video on the left is considered to be of perfect quality while the video on the right is compressed and then reconstructed with possible packet loss and concealment. Three naive human subjects are involved in this experiment. They are asked to pick a number representing the perceptual quality of the processed video compared to the perfect video from the continuous quality scale shown on the left end of Figure 6. 50 video pairs were tested and 20% of them appear twice in this experiment to test the consistency of the subjects' decisions.

Figure 6 plots the opinion scores given by the three subjects. We find the best linear fit of average PSNRs across all the frames for each video tested and $PSNR_{r,f}$ with f ranging between 0.5 to 0.99, according to minimum mean square error. The best fits for average PSNR and $PSNR_{r,f=90\%}$ are plotted in Figure 6. As seen from these plots $PSNR_{r,f=90}$ correlates significantly better than average PSNR to the perceptual quality for all three videos. Average PSNR underestimates the quality at high quality level and overestimates the quality at low quality level. This is because average PSNR treats all frames equally, so at high quality level, only a few frames with relatively lower quality bring down the average PSNR but do not affect the perceptual quality. While at low quality level, there are frames with extremely bad quality while the average PSNR is still quite high. This subjective experiment

(a) $QP = 26, fading@7dB, avgPER = 5.5\%$

(b) $QP = 26, AWGN@3dB, avgPER = 1.5\%$

(c) $QP = 30, fading@7dB, avgPER = 5.5\%$

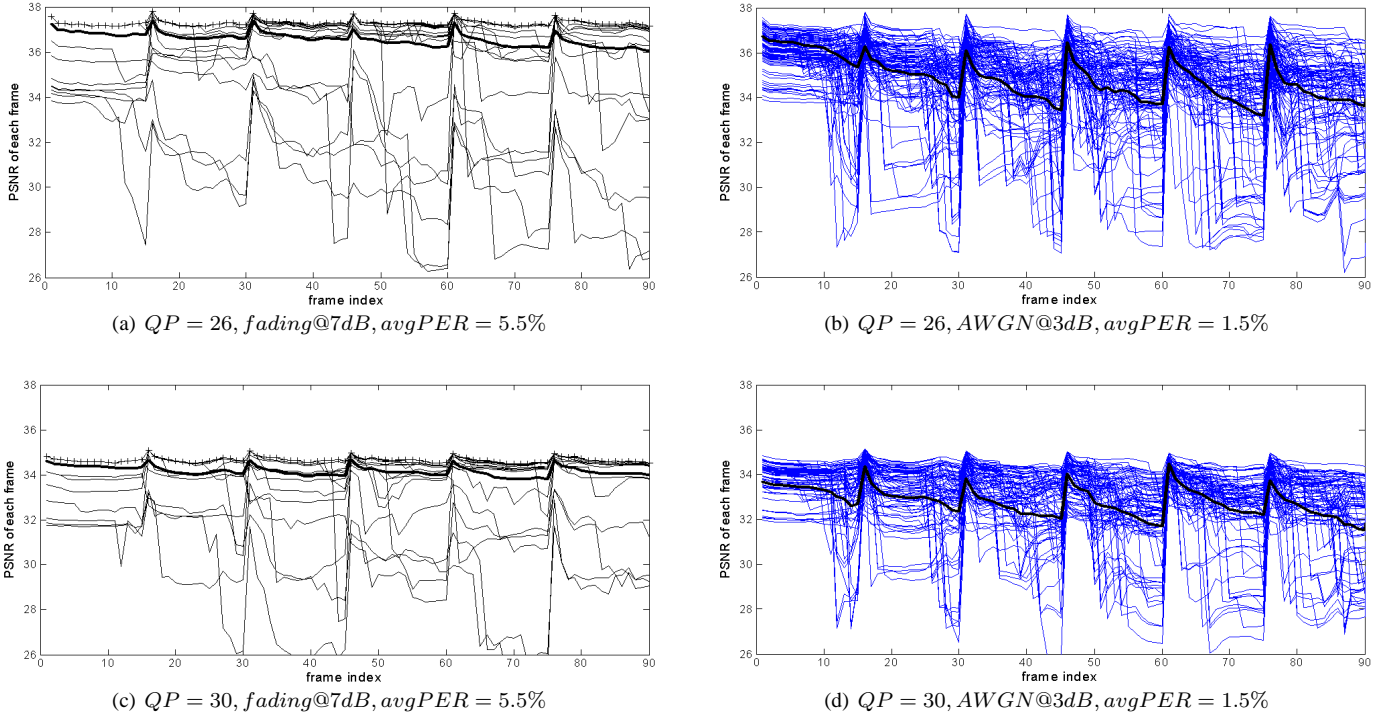(d) $QP = 30, AWGN@3dB, avgPER = 1.5\%$

Fig. 5. PSNRs of each frame of the video silent.cif coded at GOPS = 15, PS = 100 for 100 realizations of multipath fading channel of average SNR 7 dB and AWGN channel of SNR 3 dB respectively, when PHY data rate 6 Mbps is used. The thick lines in each plot represent the average PSNRs across the 100 realizations which are represented by the other lines.

implies that $PSNR_{r,f}$ can serve as an effective video quality measure before more sophisticated perceptual quality measuring methods come along, and that f should be set around 90% for medium video frame rates, such as 15 fps used in this paper.
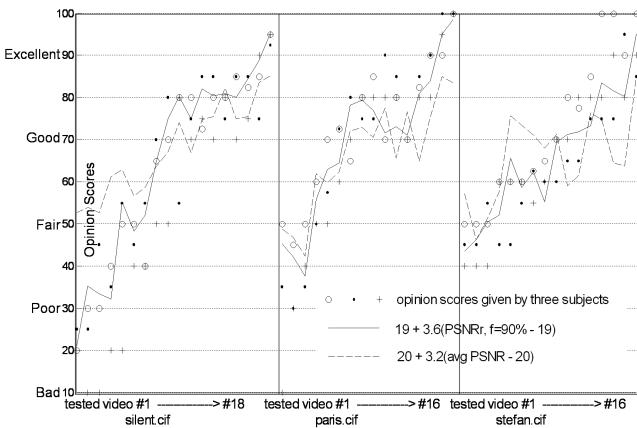

Fig. 6. Scale and results of subjective experiment

V. DISCUSSIONS

$PSNR_{r,f}$ has the potential to capture the performance loss due to damaged frames in a video sequence ($f\%$), as well as to indicate how often a user, in multiple uses of the channel, would experience a specified quality ($r\%$). Figure 7 plots $PSNR_{r,f}$ for the four plots in Figure 5, with fixed

$r = 85\%$, PHY data rate = 6 Mbps, channel SNR = 7 dB over the multipath fading channel, PS = 100 bytes, GOPS = 15 and the video silent.cif. The average PSNRs displayed in this figure are calculated across all the frames of all realizations. This figure shows clearly the delivered quality guaranteed for 85% of the users for different percentage of the frames. Even though the AWGN channel in this plot has a lower channel SNR than the fading channel, from Figure 5 we can see that the AWGN channel at 3 dB has an average PER of 1.5%, which is much lower than that of the fading channel at 7 dB, 5.5%. Note that the 85% realizations that are chosen for different values of f are not always the same, and therefore in our definiton the parameter r has certain dependence on the parameter f.

Figure 8 shows $PSNR_{r,f}$ for different videos, with fixed f = 80%, PHY data rate = 6 Mbps, average channel SNR = 7 dB and QP = 26, GOP = 10 and PS = 100. This figure shows that even though the average PSNRs across all the frames and realizations for all the videos at both PSs are between 32 dB to 36 dB, which imply good perceptual quality, the PSNRs achieved by 80% of the frames in 90% of the realizations are less than 26 dB for the multipath fading channel which corresponds to poor quality. With all the parameters kept as the same, stefan.cif, which is a video of a tennis player playing tennis, is the most difficult to conceal. Silent.cif which is a head-and-shoulders video is the easiest to conceal and paris.cif with two people talking to each other falls in between the other two videos in terms of motion content and performance with packet loss concealment. Some insights into comparing
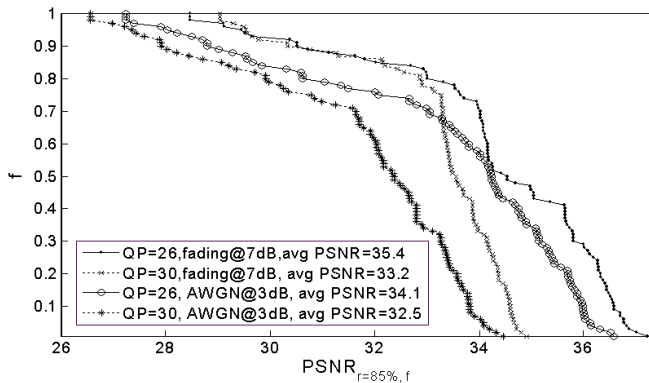
Fig. 7. Comparing $PSNR_{r,f}$ for different QPs and channel conditions, with fixed r=85%, PHY data rate = 6 Mbps, average channel SNR = 7 dB, PS = 100, GOPS = 15 and the video processed is silent.cif

AWGN and multipath fading channels are also provided by this plot. Since the fading channel delivers a certain percentage of the videos without any packet loss, its performance is always better than that of a comparable AWGN channel up to a threshold value for r, about 70% in this specific case. On the other hand there are also very bad realizations for the fading channel. As can be seen from Figure 4, about 8% of the realizations for PS = 100, fading channel at 7 dB have PLR greater than 20%. Returning to Figure 8, when r is greater than 92%, the performance of AWGN channel is definitely better than a comparable multipath fading channel. When r falls between 70% and 92%, i.e., when the fading channel realizations have PLR greater than 0% but less than 20% from Figure 4, we can see in Figure 8 that as r increases, the quality of delivered video over the fading channel decays faster than that over the AWGN channel. The interplay of the coding parameters on the processed video quality are discussed in [16].
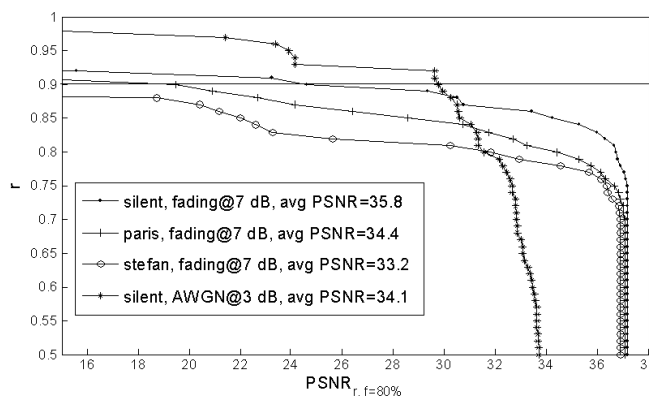

Fig. 8. Comparing $PSNR_{r,f}$ for different videos and PSs, with fixed $f = 80\%$, PHY data rate = 6Mbps, channel SNR = 7dB and QP = 26, GOP = 10

VI. Conclusions and future work

In this paper we investigate the delivered quality of AVC/H.264 coded video across the video characteristics, the quantization parameter (QP), the group of picture size (GOPS),

the payload size (PS), PHY data rate in 802.11a, and average channel signal to noise ratio (SNR), for AWGN and multipath fading channels. We show that for the same video coded using the same parameters for the same average channel SNR, the quality of concealed video varies significantly across different realizations. The PSNRs also vary from one frame to another in the same processed video sequence. Neither the average PER nor the average PSNR across all the frames and all the realizations, is a suitable indicator of the quality a video user experiences and therefore they should not serve as the basis for video communications quality assessment.

We define a statistical video quality indicator $PSNR_{r,f}$ as PSNR achieved by $f\%$ of the frames in each one of the $r\%$ of the realizations. We show that $PSNR_{r,f}$ agrees consistently with perceptual video quality through a subjective experiment. We employ $PSNR_{r,f}$ to evaluate video communications performance under various channel conditions and to select the best combination of codec parameters at certain desired consistency of video user experience.

Future work will include more subjects in the subjective experiment to construct a nonlinear relationship between the opinion scores and $PSNR_{r,f}$.

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